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Real-time Estimation of Resistivity Anisotropy Using Array Lateral and Induction Logs

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Abstract

Conventional resistivity tools often miss hydrocarbon pay zones in thinly laminated sand-shale sequences. Incorporation of formation resistivity anisotropy into a petrophysical model allows for a significantly more accurate means to estimate hydrocarbon reserves in low-resistivity reservoirs. To correctly determine the anisotropy distribution around the borehole, an interpreter must use the multi-component induction logs acquired with the application of the new 3DEX tool.

If the multi-component induction measurements are not available, an interpreter should consider some alternative ways to determine anisotropic properties of the formation.

In this paper, we propose two new methods to estimate resistivity anisotropy using vast logging data from the Array Lateral Log (High-Definition Lateral Log - HDLL) and Array Induction Log (High-Definition Induction Log – HDIL) tools:

- The first method is based on a sequential interpretation of the HDIL and HDLL data. It does not require layer selection for formation model definition. It is very fast because it uses sequential induction and galvanic data processing as well as short inversion windows.

- The second method utilizes borehole-corrected lateral resistivity (LR) logs and vertical resolution matched (VRM) focused logs. The method does not require application of inversion-based processing and provides anisotropy values at every logging point. This approach is extremely fast.

We evaluate and compare the anisotropy interpretation results derived from the application of these methods. We use a 150-foot portion of a single data set acquired in a vertical offshore well in the Mediterranean region. This unique logging data set contains various different array resistivity logs. We show that both methods supply an interpreter with anisotropy estimates within time limits imposed by real-time well-site processing.

Background

A significant part of the world's estimated hydrocarbon reserves is contained in thinly-bedded, low-resistivity formations containing hydrocarbon producing laminar sands. In these formations, the transverse (vertical) resistivity, R_v, perpendicular to the bedding plane is greater than the longitudinal (horizontal) resistivity, R_h, parallel to the bedding plane. This dependence of resistivity on the direction of current flow is called anisotropy.

The anisotropy coefficient is defined as a ratio of R_v over R_h:

$$\lambda = \frac{R_v}{R_h}$$

The traditional laminar shaly sand saturation equations are based on a simple parallel conductivity model that typically results in significant underestimation of hydrocarbons-in-place. The resistivity anisotropy based interpretation methods, when combined with petrophysical analysis, lead an interpreter to a better identification and a more accurate quantification of hydrocarbon reserves.[1]

An accurate determination of formation anisotropy could be achieved via the application of unique multi-component induction (3DEX) technology. This approach was developed to provide both improved identification and quantification of hydrocarbons. Our 3DEX tool provides all necessary data to accurately compute both horizontal (R_h) and vertical (R_v) resistivities.[1-4] Enhanced shaly sand reservoir characterization models utilizing multi-component induction data lead interpreters to a significant increase in the estimates of hydrocarbons-in-place.[1]

If the multi-component induction measurements are not available, or if use of this instrument under given environmental conditions is not recommendable, an interpreter should consider alternative ways to determine the anisotropic properties of the formation.

The effect of formation anisotropy on conventional resistivity measurements have been well studied in numerous publications.[5-7] In near-vertical wells, logging tools such as Dual Laterolog (DLL) or Array Induction generate currents primarily parallel to the formation bedding layers, and are thus not sensitive to changes of the formation resistivity in the

vertical direction. Therefore, even a joint interpretation based on DLL-type, galvanic logs and array induction-type logs[6, 7] cannot generally provide reliable anisotropy estimates.

On the other hand, the lateral-type, unfocused log contains information related to both horizontal (R_h) and vertical (R_v) resistivities. Moreover, if we neglect the effects of both the borehole and the invaded zones, an anisotropic bed can be replaced by an equivalent isotropic bed describable with the following parameters[5]:

$$h_{eq} = \sqrt{\lambda}\ h \qquad (1)$$

$$R_{eq} = \sqrt{\lambda}\ R_h \qquad (2)$$

In (1) and (2), h and R_h are the true formation thickness and resistivity, respectively; h_{eq} and R_{eq} are equivalent formation thickness and resistivity, respectively; and λ is the anisotropy ratio.

This beautiful equivalence immediately suggests several alternative approaches to estimate formation anisotropy. These include using an unfocused lateral log in combination with additional logs providing accurate information about true formation thickness and horizontal resistivity.

One approach is based on the joint 2-D inversion of lateral and induction logs.[8] For the first step, the author suggests recovering the true layer thickness h and its horizontal resistivity R_h by using an induction log. For the second step, and to calculate the anisotropy ratio, the author uses the results of the first step combined with results from a lateral log inversion.

The method[8] was tested on three-layer models using only conventional lateral and induction synthetic logs. There are several shortcomings to this approach. Firstly, the practicality of this method will require careful layer picking. Secondly, to determine an accurate R_h, an interpreter must carry out the inversion of an induction log. Thirdly, the limited number of conventional galvanic and induction logs available when using this method may not provide enough data for a more accurate estimation of formation anisotropy.

In the following sections of this paper, we first briefly describe the family of available array resistivity tools. Next, we describe our two new methods for calculating formation resistivity anisotropy. Finally, we test these methods on a single well logging data set consisting of several different array logs. We then demonstrate that these methods can provide real-time anisotropy estimates even in difficult field situations.

Array Resistivity Tools (HDIL, HDLL, 3DEX)

The HDIL is an array induction tool that collects data at multiple frequencies and various transmitter-receiver spacings.[9] This tool utilizes only vertical transmitter and receiver array coils (the coil centers are in line with the tool axis). Therefore, the induced current in near-vertical wells is dominated by its horizontal component, and the induction data contains information related to R_h alone.

Existing focusing algorithms are designed to convert the HDIL measurements into so-called Vertical Resolution Matched (VRM) logs. In shaly-sand type reservoirs, the deep-reading VRM curves read close to R_h.[10]

The HDLL is an array-type, unfocused galvanic logging tool. It has a single current injection electrode. The tool measures an array of the absolute potentials and the first differences at selected receiver electrodes. On the basis of the measured first differences, a set of lateral resistivity (RL) logs are computed.

In near-vertical wells drilled with conductive drilling muds, the HDLL instrument provides vertical resolution and resistivity invasion profiles similar to those provided by array induction tools in oil-based mud.[11] Since the injected current has both horizontal and vertical components, the acquired data contains information related to both horizontal (R_h) and vertical (R_v) resistivities.

The 3DEX tool employs sets of Z direction coils coaxial with the instrument in addition to orthogonally mounted X and Y direction coil arrays. This setting provides measurements of five components: H_{xx}, H_{yy}, H_{zz}, H_{xy}, and H_{xz} at seversal frequencies.

Inversion processing of 3DEX induction data then allows the computation of both horizontal (R_h) and vertical (R_v) resistivities. In turn, this leads to an accurate determination of the formation resistivity anisotropy ratio, λ. The incorporation of such induction data interpretation results into an enhanced shaly-sand, tensor resistivity petrophysical analysis leads to much reduced evaluation uncertainties. The inclusion of multi-component induction data may thus result in a significant increase in calculated hydrocarbon-in-place reserves over estimates obtained with conventional methodologies.[1]

Anisotropy Estimation by Inversion of the Array Lateral and Induction Logs

It is well-known that the deep-reading, borehole-corrected VRM curves read R_h quite accurately in shaly sands.[10] Therefore we do not have to run the array induction data inversion but assume that R_h = VRM. To make the anisotropy estimation process automatic and robust, we suggest squaring the deepest reading VRM curve based on a constant layer thickness.

We then use this model as a starting point and proceed to invert the selected lateral logs. This 2-D inversion allows us to correct the data for borehole, invasion, and shoulder bed effects. As output of this process, we obtain parameters of equivalent isotropic layers.

Finally, we can determine λ from equation (2) by using R_h derived from the array induction logs, and R_{eq} derived from the array lateral logs.

It should be noted that application of a short overlapping inversion windows makes the process extremely fast (less than one minute/100 feet of data on SunBlade100).

Anisotropy Estimation with Corrected Array Lateral and Induction Logs

The method described in the previous section can be simplified and accelerated. As before, we get R_h from the deep-reading, borehole-corrected VRM curve. Then, instead of running the 2-D inversion of the lateral logs, we perform

chart-based log correction for the borehole and, if necessary, invasion effects.

To estimate the formation anisotropy, we use the following approximate formula:

$$\lambda = \left(\frac{RL}{VRM}\right)^2$$

The calculations are performed at each logging point. This provides a continuous anisotropy output log. The method should thus furnish reasonable anisotropy estimates in thick sand/shale formations where the borehole-corrected RL logs are not significantly influenced by significant shoulder bed effects.

In the next section we present a case study that illustrates the practical application of our proposed new methods.

A Case Study

Multi-component induction (3DEX) and conventional wireline array resistivity logs (HDIL and HDLL) were acquired in a vertical offshore well in the Mediterranean region. The well was drilled into a deep marine turbidite sequence. It encountered significant volumes of thinly bedded, laminar silty shales as well as high porosity gas sands deposited over very high quality, massive channel and turbidite fan sands.

In Fig. 1, we present the 2-D inversion results for a 150-foot interval, 600-750 ft (depths are relative). The left track (1) shows the Caliper and GR logs.

Tracks (2-3) show R_h and R_{eq} estimated from HDIL and HDLL, respectively, using the two methods presented in this paper. The separation between R_h and R_{eq} is evident in both right tracks, and indicates the degree of formation resistivity anisotropy within this interval.

It should be noted that inversion-based processing with short, sliding down windows takes less than 1.5 minute on a SunBlade100 computer.

In Fig. 2, we present the results of anisotropy estimation with our methods. We also compare these results with the reference anisotropy model we derived with the accurate 3DEX/HDIL data inversion method.[2] The step-wise curves were smoothed out and we present them as continuous logs.

The left two tracks show the Caliper, GR, Density, and Neutron logs. Track (3) shows a comparison between the anisotropy factor, AF1, derived with our first method versus the reference anisotropy factor, AF2, derived from application of the multi-component induction data. We recall that the first method is based on HDIL-focused data and HDLL 2-D inversion.

Track (4) shows the comparison between the anisotropy factor, AF1, versus the anisotropy factor, AF3, derived from our method based on the correction of the HDIL-focused logs and HDLL lateral logs.

These comparisons show a reasonable match between the anisotropy factors, AF1 and AF2, along the entire interval, except in the 710–725 feet section, where the reference anisotropy gives higher values. The match between the anisotropy factors AF1 and AF3 is worse than between anisotropy factors AF1 and AF2. This could be attributed to the influence of the uncorrected shoulder bed effect on the RL log, which might well affect the AF3 estimates.

Our results provide us with a practical validation of the proposed methods, and lead to the following conclusions.

Conclusions

We find the following:

- The multi-component induction (3DEX) technology provides the most accurate method to determine formation resistivity anisotropy.
- Joint interpretation of the Array Induction (HDIL) and Array Lateral Log (HDLL) data can be used as an alternative way to estimate formation resistivity anisotropy.
- The anisotropy interpretations obtained with our proposed methods are in reasonable agreement with an independent anisotropy interpretation based on the direct inversion of multi-component induction data acquired in the same well.
- The methods are fully automatic and can be used in situations when superior multi-component induction data is not available.
- The methods could be used for the reprocessing of previously acquired induction and lateral logs.

Future developments should include:

- Expansion of the methods to more complicated, invaded-type formation models.
- More rigorous evaluation of the methods for both synthetic models and for additional field cases.

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Nomenclature

h = *True thickness of anisotropic layer, m*
h_{eq} = *Thickness of equivalent isotropic layer, m*
R_h = *Horizontal resistivity of anisotropic formation, Ohm-m*
R_{eq} = *Resistivity of equivalent isotropic formation, Ohm-m*
R_v = *Vertical resistivity of anisotropic formation, Ohm-m*
RL = *Lateral Resistivity curve, Ohm-m*
VRM = *Vertical Resolution Matched curve, Ohm-m*
λ = *Anisotropy ratio*

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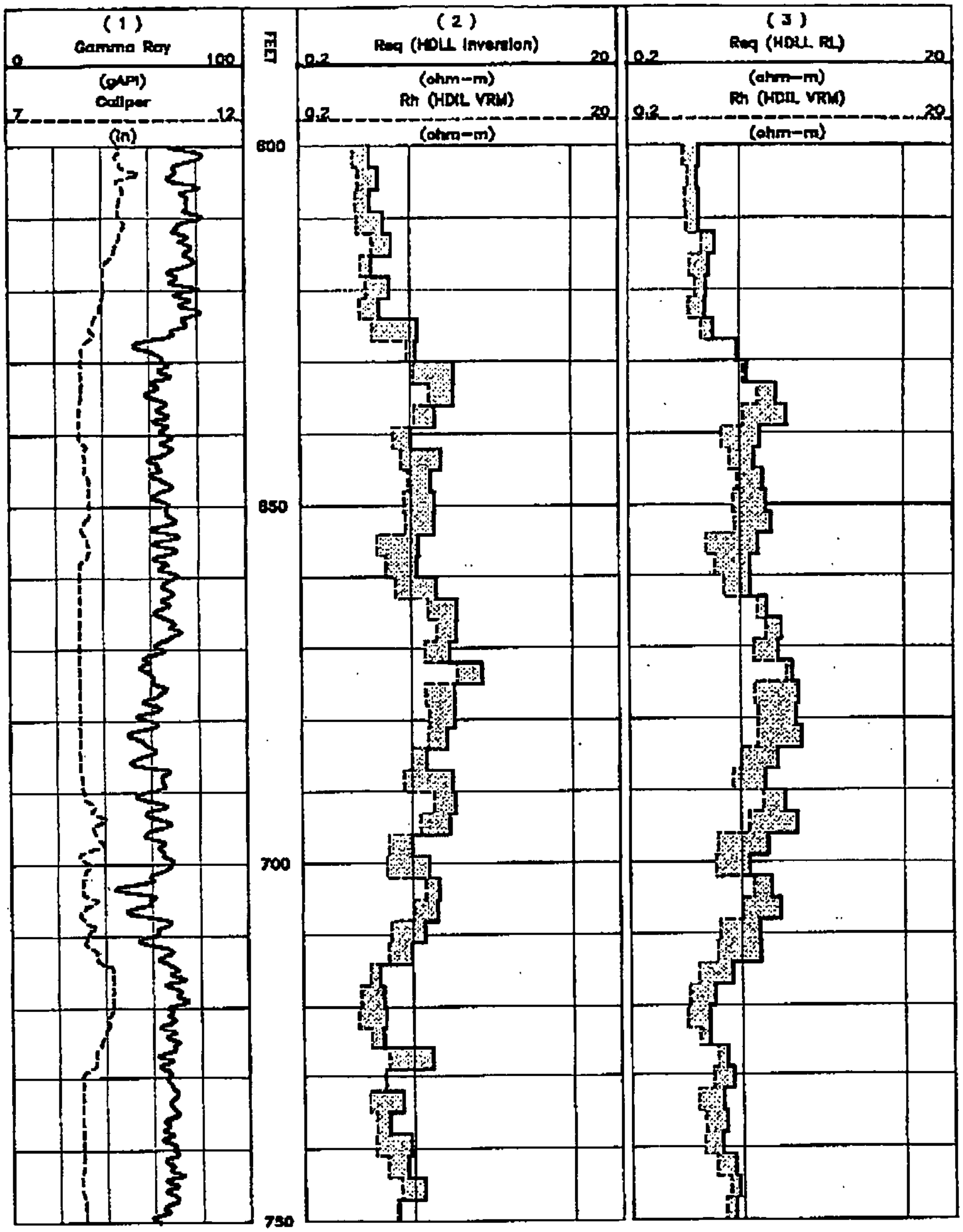

Fig. 1: The 2-D inversion results for a 150-foot interval in a vertical offshore well in the Mediterranean region. Tracks (2-3) show Rh and Req estimated from HDIL and HDLL, respectively, using the two methods presented in this paper. The separation between Rh and Req is evident in both right tracks, and indicates the degree of formation resistivity anisotropy within this interval.

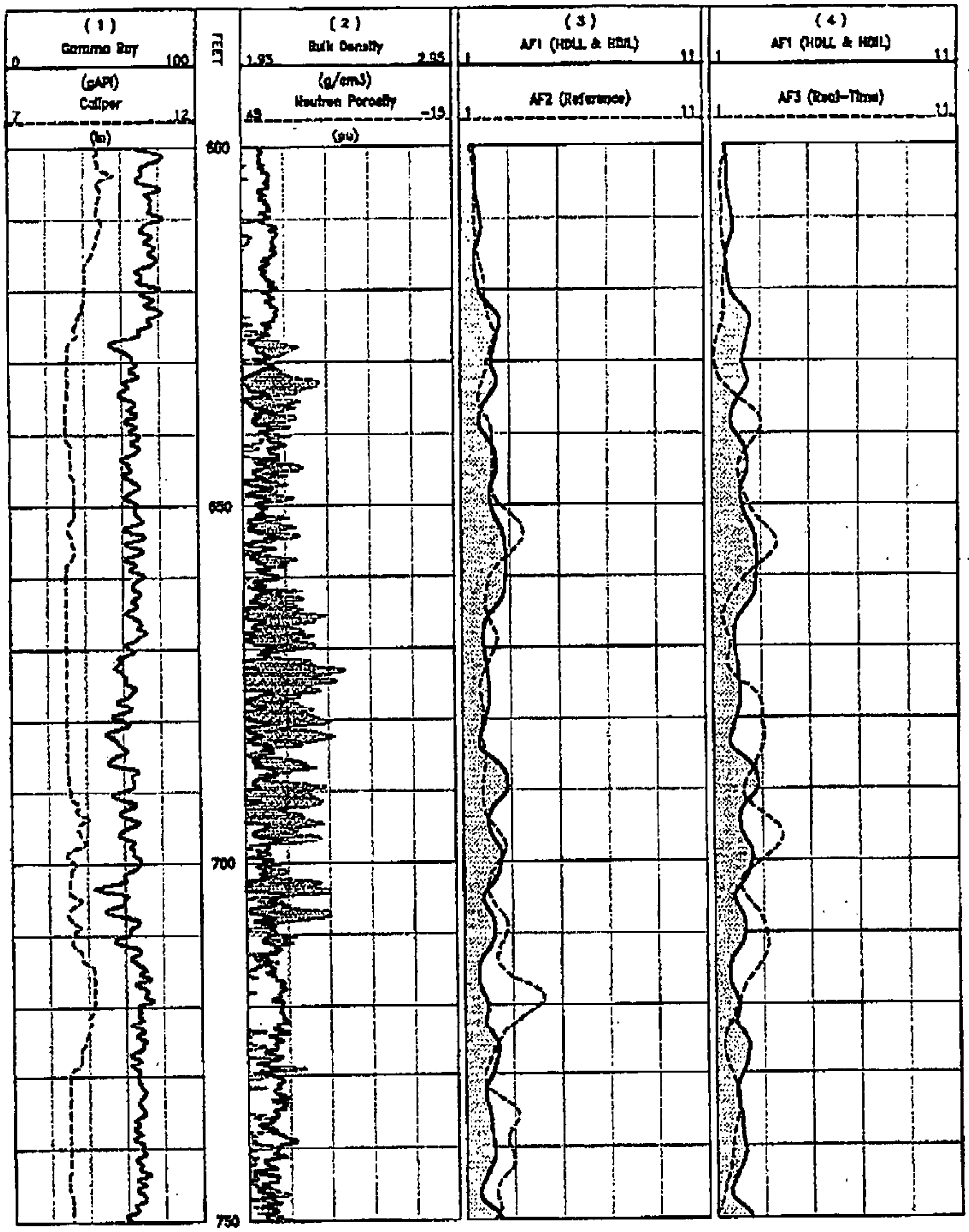

Fig. 2: Comparison of the results of anisotropy estimation using the two methods presented in this paper (AF1 and AF3 logs) with the anisotropy estimation derived with the accurate multi-component induction data inversion method (AF2 log).